Atmospheric Scattering Effect on Spatial Resolution of Imaging Systems

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ABSTRACT

In this paper a physical model that describes the relationship between the optical properties of the atmosphere and the characteristics of an imaging system is suggested. The model describes how different components of the light reaching the imaging system, after passing through the atmosphere, are detected by it. The model includes the effects of the final size of the detector elements of the imaging system and the dynamic range and the final field of view limits of the imager. It is found that for common imaging systems (with resolution of 8bit or 12bit) working in general atmospheric conditions (VIS≥5km), the processes of atmospheric scattering and absorption hardly contribute to spatial blurring of the recorded images. A field experiment was carried out in order to verify the predictions of the suggested model. The measurements were performed using a scanning point radiometer, while a local meteorological station and a visibility meter measured the properties of the atmosphere. Theoretical predictions, which were accomplished by using a Monte-Carlo simulation of atmospheric scattering effects, are compared with the experimental data acquired in the field tests. A good agreement was obtained between the measured data and the theoretical predictions.

1. INTRODUCTION

Light emanating from a radiation source is scattered and absorbed by molecules and aerosols in the atmosphere. It is also deflected from it's original path by atmospheric turbulence. Some of the above phenomena give rise to reduction of the source intensity and some give rise to spatial blurring of the source radiation. The contribution of the atmospheric turbulence to spatial blurring is well known and have been characterized by many authors (see e.g. [1,2,3,4,5,6]). Since the problem of light propagation in a scattering and absorbing atmosphere has no general analytical solution, various analytical approximations have been suggested. The Small Angle Approximation (SAA), the Diffuse Approximation (DA) and the Small Angle Diffuse Approximation (SADA) [7,8,9] are some of the known analytical approximations, each having it's own range of validity. Another approximation, implemented for vertical viewing from satellites, is the two stream approximation [10, 11]. For certain simple geometries it is possible to solve the equation of radiation transfer either numerically [12, 13] or analytically [14,15,16] and to get an analytical expression for the atmospheric contribution to spatial blurring (laser beams [17]). The most general numerical technique used to calculate the effects of an arbitrary turbid atmosphere on optical systems is the Monte Carlo method [18, 19,20,2 1,22,23]. All the above mentioned methods pertain to the blurring effects of the scattering atmosphere at the focal plane of the optics but do not consider other properties of the imaging systems. Sadot and Kopeika suggested a "practical" model [24] that describes how the properties of an imaging system affect the detected radiation by considering the Modulation Transfer Function (MTF) at the image plane. The image plane (not to be confused with the focal plane) is a virtual plane that includes also the effects of the detector and the electronics of an imaging system. A comment on that model by Bissonnette [25] and the response to it by Sadot and Kopeika [26] showed that though there is a common agreement on the blurring effects of the scattering atmosphere at the focal plane, there exist a disagreement in the issue of how the scattered radiation

is detected by an imaging system. The aim of this paper is to present a physical model of the detection process of the incident radiation by an imaging system. This model allows to calculate the distribution of the detected radiation (the Point Spread Function - PSF) in the image plane. A field experiment was performed in which atmospheric scattering effect on the PSF of a scanning point radiometer was measured. Theoretical predictions of the suggested model agree well with our experimental results and the experimental results of Bissonnette.

2. THEORY

The radiation that is detected by the detector of an imaging system is composed of 3 main constituents: A) direct radiation from the source blurred by three different mechanisms, B) radiation scattered by the atmosphere and C) radiation scattered within the optical system. Here we follow the common approach to the solution of imaging problems in the atmosphere [8,17] by treating the light, that is propagating in the atmosphere, as composed of the unscattered (direct) and the scattered components. The radiation that is scattered within the optical system originates in reflections from mechanical elements and non perfect optical components and coatings. Baffles and glare stops are few of the methods to reduce this stray light, but most of the commercially available imaging systems do not have these elements in their optical design. Stray light is usually several orders of magnitude weaker than the direct radiation, therefore it is noticeable only when a strong source of light is introduced into or near the field of view of the system or in case that the imaging system has a wide dynamic range.

2.1 The Point Spread Function

The basic physical function that describes the spatial response of an optical system is the Point Spread Function - PSF. If several conditions are met in the imaging process then it possible also to describe the spatial response of the optical system in terms of its Modulation Transfer Function - MTF, the amplitude of the hi-dimensional Fourier transform of the PSF:

$$MTF(\nu_x, \nu_y) = \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} PSF(x, y) e^{-2\pi i (x\nu_x + y\nu_y)} dxdy \right| \tag{1}$$

where x and y are spatial coordinates and ν_x and V_y are spatial frequency coordinates in the focal plane. The conditions for the validity of the representation of the spatial response by the MTF are given by the linear filter theory [27]:
1.   All the steps in the process of image formation should be linear.
2.   All those steps should be isoplanatic (stationary in time and space).
3.   The imaging process should be one-to-one mapping of the input plane to the output plane.

In the spatial domain the cumulative effect of two successive optical elements in the imaging process is given by a convolution between their PSF. In the spatial frequency domain the cumulative effect is given by a regular multiplication between their MTF (a property of the Fourier transform). This decomposition of the response of two successive optical elements into multiplication between their MTF is valid only if their spatial responses are uncorrelated. The above property, which makes system analysis much simpler in the spatial frequency domain rather than in the spatial domain, is the main reason that MTF became so popular in representing the spatial response of imaging systems.

The major drawback of using MTF in representing the spatial response of imaging systems is that some of the above mentioned conditions are not valid for those systems. For example some of the light detection processes are not linear (non linearity of the detection process) and some are not isoplanatic (spatial sampling

effects). There exist a dependence between various stages in the imaging process which makes the MTF decomposition into multiplicative terms invalid (atmospheric effects on imaging systems are a function of the imaging system properties). Though there are some attempts to overcome these drawbacks [28,29] of the MTF formalism, we will consider in the following model only the basic physical function that describes the spatial response of an optical system. the PSF.

2.2 **The direct radiation**

The direct radiation from a distant point source arrives at an imaging system as a plane wave (paraxial approximation). If the optics of the imaging system was unlimited in size and no system effects were present, then this plane wave would be focused to a point (spatial delta function) in the focal plane. This spatial delta function transforms to a blurred wider distribution function when the direct radiation is passing through the optical components of the imaging system and especially when it is detected by the system's detector. There are three main blurring processes in imaging systems: optical (diffraction) blurring, blurring due to the finite size of the detector elements and the display (electronic) spatial blurring. The blurring due to electronic effects varyies from system to system and is dependent on its specific signal processing. In this paper we will describe an imaging system that has the most simple signal processing that does not add to the spatial blurring. The optical blur is due to a diffraction by a size limited optics of the system. The optical blur of a light source with a unit intensity is described by an Airy disk pattern [8]:

$$I_{OPT}(r) = \frac{D^2}{4\,r^2}\,J_1^{\,2}\left(\frac{\pi D r}{\lambda f_0}\right) \tag{2}$$

Where $I_{OPT}(r)$ is radial distribution of the radiation flux in the focal plane. λ is the wavelength of the incident radiation, D and f_0 are the diameter and the focal length of the optical system, respectively, and J_1 is the Bessel function of the first order. The first zero of the Airy disk pattern occurs at a distance r_{Airy} from the axis of the system:

$$r_{Airy} = 1.22\frac{\lambda f_0}{D} \tag{3}$$

After passing through the optics the radiation is incident on the detection system that has detection elements with finite size. The detection elements can be either elements of a focal plane array or a single/vector of scanning detectors. The distribution of the detected radiation of a unit intensity light source between those detector elements is not an ideal rectangular function with dimension of the detection element, as can be assumed if we neglect the diffraction effect. This distribution is commonly described [28,29] by a Gaussian function that depends on σ - the size of the detection element. This distribution is not the actual distribution of the radiation (which is assumed here as a spatial delta function) but an effective radiation distribution as sensed by the detection elements of the imaging system.

$$I_{DIR}(r) = \frac{1}{2\pi\sigma^2}\cdot e^{\left(-\frac{r^2}{2\sigma^2}\right)} \tag{4}$$

Where $I_{DIR}(r)$ is an effective radial distribution of the radiation flux in the focal plane. σ is the typical size of the detection element and is related to the IFOV - Instantaneous Field Of View of the system and to its focal length f_0 - by:

$$IFOV = \arctan\left(\frac{\sigma}{f_0}\right) \cong \frac{\sigma}{f_\theta} \tag{5}$$

This approximation is valid here since the IFOV is usually a very small angle. The above radiation distributions are integrated over the detector element area, and hence they should be multiplied by σ^2 to yield the detected signal by the system. Since the atmosphere absorbs the radiation and scatters it out of the line of sight, then the measured signal will be obtained by multiplying the above distributions of a unit intensity light source by $T = e^{-\tau}$, where T is the atmospheric transmittance and τ is the optical depth of the atmosphere. For most of the imaging systems the spatial resolution is limited by the final size of the detection elements ("detector limited" case where $r_{Airy} << \sigma$) and not by the diffraction limit of the optics ("diffraction limited" case where $r_{Airy} >> \sigma$). Analysis of a diffraction limited imaging system operating in a turbid medium is given by Ishimaru [30]. In this paper the spread of the direct radiation as detected by an imaging system will be modeled by considering a detector limited system (and the diffraction effect will be neglected). Hence the detected signal of a unit intensity light source will be described by the product of the terms of Eq. 4, atmospheric transmittance and the area of the detector element:

$$PSF_{DIR}(r) = I_{DIR}(r) \cdot e^{-\tau} \cdot \sigma^2 = \frac{e^{-\tau}}{2\pi} \cdot e^{\left(-\frac{r^2}{2\sigma^2}\right)} \qquad (6)$$

In a general case neither of the blurring effects is neglected and the PSF relative to the direct radiation is given by a convolution between the terms in Eq. 2 and 4. It is important to note here that the above described direct radiation distribution is what is usually referred to as the imaging system PSF. Depending on the system properties, this imaging system PSF may also include the contribution of the radiation which is scattered within the imaging system.

2.3 The radiation scattered by the atmosphere

The light emanating from the radiation source is scattered and absorbed by molecules and aerosols in the atmosphere. Various analytical and numerical solutions exist for the problem of radiation transfer in the atmosphere. In the present work a modified version [31] of the SEMIM [21,22,23] Monte Carlo code is used to evaluate the contribution of atmospheric turbidity to the augmentation of the Point Spread Function. SEMIM code output was successfully compared [21] with published data from controlled laboratory measurements by Donelli et al. [32] and by Kuga and Ishimaru [33,34]. The scattered radiation reaching the imaging system is a function of the view angle in the lens plane, θ (see Fig. I):

$$\tan(\theta) = \frac{r}{f_0} \qquad (7)$$

However in order to obtain the detector signal PSF_{SCA} this radiation should be integrated over the solid angle subtended by the detector element of the imager, and hence it should be multiplied by $IFOV^2$ (or by $(\sigma/f_0)^2$ - see Eq. 5):

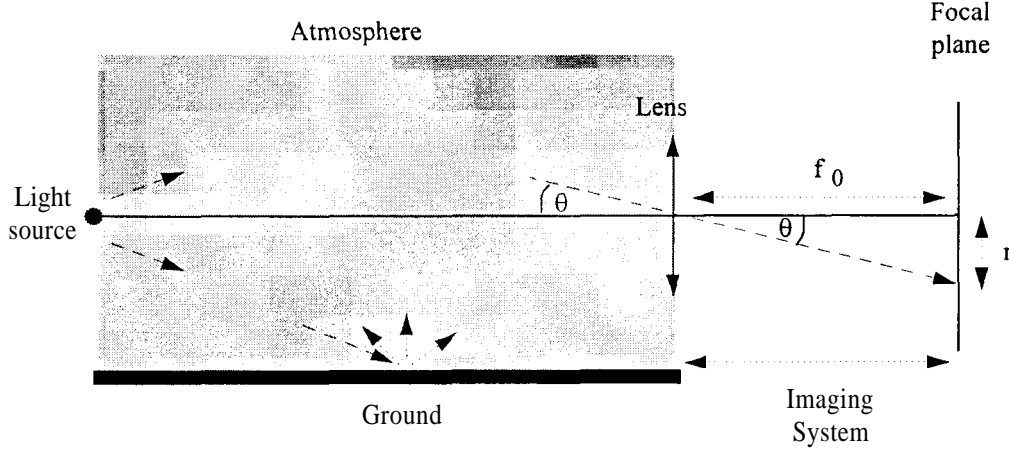$$PSF_{SCA}(r) = I_{SCA}(r/f_0) \cdot (\sigma/f_0)^2 \qquad (8)$$

Figure 1: Geometry of an imaging system looking at a point source through the intervening atmosphere.

where $I_{SCA}(r/f_0)$ is the angular distribution of the scattered radiation (in Watt/str) that is obtained through the Monte-Carlo method as will be described later. This equation is based on the assumption of a constant IFOV for all detector elements (based on the paraxial approximation of $r \ll f_0$). For imaging systems with short focal length this assumption may not be valid and a $\cos^3(\theta)$ correction factor for the projected IFOV should be applied:

$$PSF_{SCA}(r) = I_{SCA}(r / f_0) \cdot \frac{\sigma \cdot \sigma \cos(\theta)}{\left[f_0 / \cos(\theta)\right]^2} = I_{SCA}(r / f_0) \cdot \frac{\sigma^2}{f_0^2} \cdot \left(\frac{f_0 f_0}{\sqrt{r^2 + f_0^2}}\right)^3 \tag{9}$$

2.4 The model for the detected light

In the theoretical model presented herein we try to quantify the relative contributions of the scattered and the direct radiation components to the spatial distribution of radiation from a point source as detected by an imaging system. We assume a linear imaging system and the input radiation to the system is the sum of two independent components (scattered and unscattered radiations). Hence the detected signal is the sum of the two detected components:

$$PSF_{DET}(r) = I_{SCA}(r / f_0) \cdot \frac{\sigma^2}{f_0^2} \cdot \left(\frac{f_0}{\sqrt{r^2 + f_0^2}}\right)^3 + \frac{e^{-\tau}}{2\pi} \cdot e^{\left(-\frac{r^2}{2\sigma^2}\right)} \tag{lo}$$

Using the angular presentation, the above distribution is given by:

$$PSF_{DET}(\theta) = I_{SCA}(\theta) \cdot IFOV^2 \cdot Cos^3(\theta) + \frac{e^{-\tau}}{2\pi} \cdot e^{\left(-\frac{\theta^2}{2 \cdot IFOV^2}\right)} \tag{11}$$

The internal system scattered radiation is a third term that is usually present in Eq. 10 and 11. However, this term is very dependent on the specific properties of the imaging system and it is quite hard to model it properly.

2.5 Theoretical calculations

A modified version of the SEMIM Monte Carlo code is used in the present work to evaluate the contribution of atmospheric turbidity to the augmentation of the Point Spread Function. The effect of atmospheric turbidity is evaluated in the SEMIM code as due to the presence of scatterers (the secondary sources) whose defocused images are distributed on the image plane of the primary source. The positions of the scatterers are determined by a Monte Carlo procedure, while the contribution of each secondary source to the irradiance on the image plane is evaluated by means of Geometrical Optics.

Several simulations were performed in order to investigate the effects of atmospheric scattering and absorption on the spatial resolution of imaging systems. The calculations were done for a CCD camera operating in the visible spectral region (0.55 pm). The size of a detector element was chosen to be 15 μm and a number of detectors in the array is 512 detectors (these numbers are typical for a commercial available CCD cameras). The diameter of the lens was kept constant at 4 cm and the focal length of the optics varied between 1 cm (a system with a wide field of view - 38 deg) to 100 cm (a system with a narrow field of view -0.44 deg). Figures 2a and 2b presents the calculated normalized PSF (using Eq. 10 and dividing by PSF(0)) of this imaging system for a point lambertian source located 1 km horizontally from the system for the rural and radiation fog aerosol models, respectively. The atmospheric parameters used in the above simulation were calculated [31] using the data of the size distributions and the retractive indices of atmospheric aerosols, tabulated in the report by Shettle and Fenn [35], and by using the LOWTRAN7 code [36],
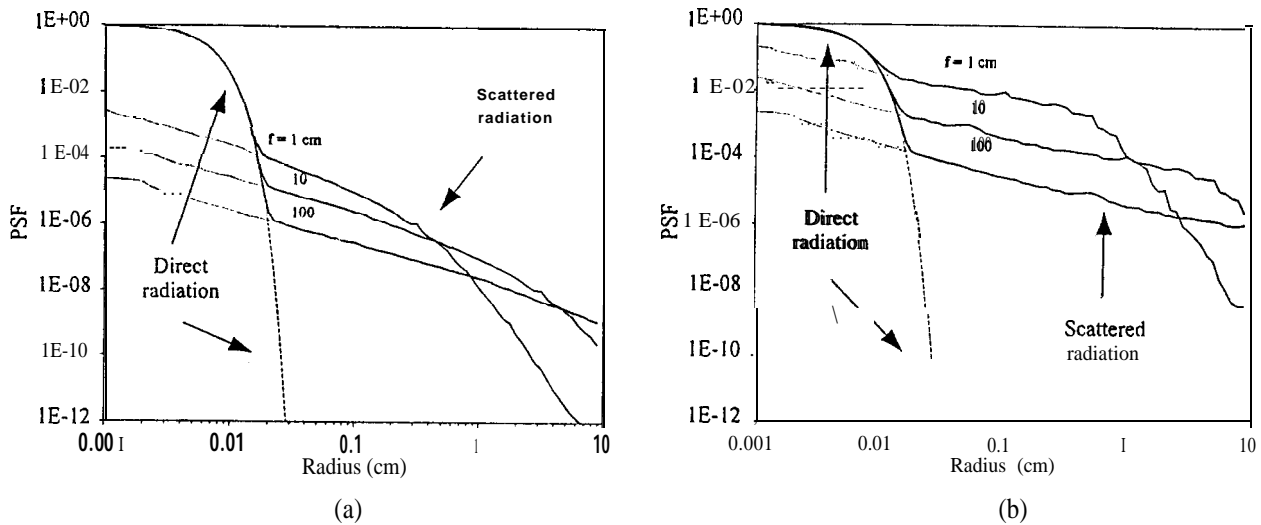

Figure 2: Simulated normalized PSF of an imaging system operating in the visible wavelength for 3 different focal length's = 1, 10 and 100 cm. The aerosol models used are: (a) Rural aerosol (VIS = 5 km); (b) Radiation fog (VIS = 0.5 km).

As one can see, the common feature in figure 2 is the increase in the contribution of the scattered radiation to the PSF when the field of view becomes wider (smaller focal length). Common imaging systems have a dynamic range with about 2-4 orders of magnitude (8 bits = 1:256 to 12 bits = 1 :4096). Due to this technical limitation the curves in figure 2a shows that for most common viewing conditions in the atmosphere and for most common types of imaging systems, the atmospheric scattering will not have any effect on spatial blurring of the images. Only at very extreme atmospheric conditions (such as dense fog, rain or sand storm) imaging systems with wide FOV will produce somewhat blurred images due to atmospheric scattering. At this point it is important to note that atmospheric scattering and absorption have a strong influence on the reduction of the contrast of the objects seen through the atmosphere in most of atmospheric conditions (see

Fig. 3). This contrast reduction must not be confused with spatial blurring, which, as was shown here, is not influenced usually by atmospheric scattering and absorption.
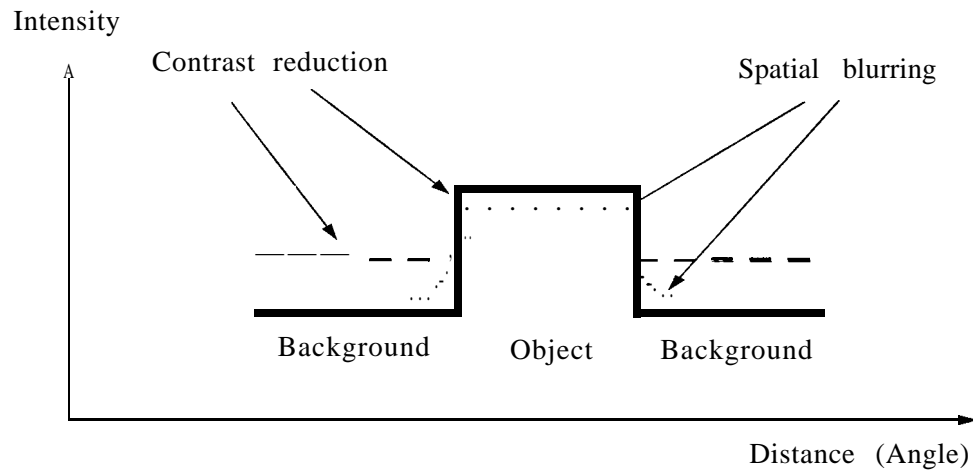
Intensity

Figure 3: Visualization of the differences between two different atmospheric effects : Contrast reduction and Spatial blurring. The thick line represents a spatial (angular) scan over the object in the object plane, and the dashed/dotted lines are the scans over the object in the optics plane. which includes the atmospheric effects.

3. EXPERIMENTAL SETUP

The basic instrument that we used in the field tests that we performed was a scanning point radiometer. This instrument was chosen since it does not suffer from most of the drawbacks of regular imaging cameras: It has a large dynamic range and almost an unlimited angular region. Figure 4 describes the general geometry of the field test: Two radiometers together with the meteorological station and the visibility meter were placed on a roof of one building, and a strong quartz halogen lamp was placed on the roof of another building 650 meters away. The PSF was measured by using that lamp as a point source. The effects of turbulence were minimized by choosing the optical path to be about 50m above the ground.
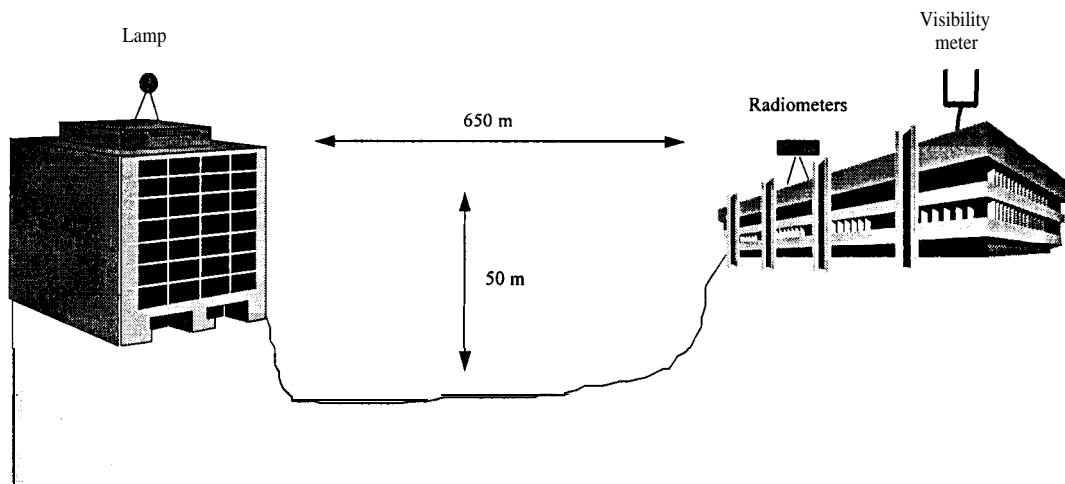

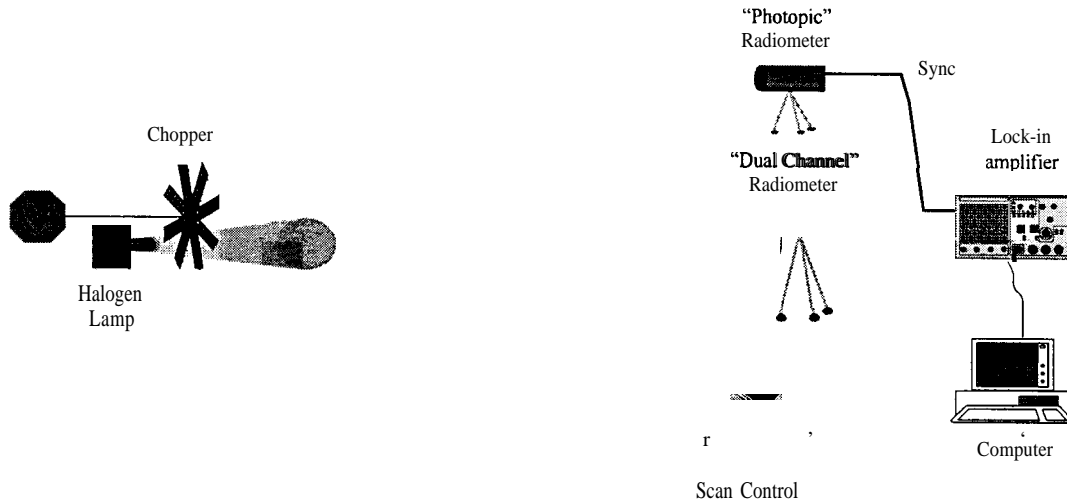Figure 4: General geometry of the field experiments.

Figure 5: The experimental setup.

Figure 5 shows the experimental setup that was used in the measurement of the PSF: As a light source a 250W quartz halogen lamp was used with a divergence of about ±30°. The radiation from the lamp was chopped by a mechanical chopper at 280 Hz. In order to detect only the chopped radiation three SR-850 lock-in amplifiers were used. The reference signal to the lock-in amplifier was obtained from a second fixed "Photopic" point radiometer that monitored the frequency of the chopper. The main instrument that we used was a "Dual Channel" point radiometer (FOV = 2 mrad, $\lambda = 0.87 \pm 0.17$ μm with low-noise Si detector) that was placed on a precise scanning mechanism (1.5 deg in 5 minutes). Three SR-850 Lock-in amplifiers measured (at different amplifications) the output of the Si detector and their amplified signals were sampled by a computer. Since each one of the lock-ins has a dynamic range of 2.5 a total dynamic range of 6 orders of magnitude was covered by them. The meteorological station measured the temperature of the air, pressure, relative humidity. The scattering coefficient of the aerosols ($k_e^t \approx 3.0/VIS$) was measured by the visibility meter (model HSS-500).

4. RESULTS

A series of field measurements were performed in April-May 1996 in Haifa, Israel. Since we did not had an aerosol PMS (particle measurement system), a rough estimation of the aerosol type and size distribution was carried out. Usually an urban aerosol model was used (with the modifications of the local relative humidity), except on several days, when an eastern wind brought aerosols from the inland: On those days the rural aerosol model seemed to be a more suitable model. The details of aerosol models in the report by Shettle and Fenn [35] were used for the simulation of the predicted signal. The contribution of the radiation that is scattered inside the radiometer (system scattered radiation) was measured by placing the lamp a distance of 70 meter from the radiometer. The contribution of atmospheric turbulence, for the hottest day in the experiment, was estimated by the IMTURB model [37] to be about 0.015 mrad. Since the field of view of the radiometer was 2 mrad, the effects of atmospheric turbulence could be neglected.

Figures 6a, 6b, 6c and 6d presents a comparison between the PSF as measured by the "Dual Channel" radiometer and the predicted PSF according to model described in section 2.4. In each figure the measured data (0) appears together with 3 theoretical curves: A) the predicted direct ($PSF_{DIR}(\theta)$ with a square field of view was used in the model) combined with the system scattered radiation (. . . . .), B) the predicted direct and atmospheric scattered radiation (___) and C) the predicted signal which is composed of the sum of the direct, system and atmosphere scattered radiations (━━━).
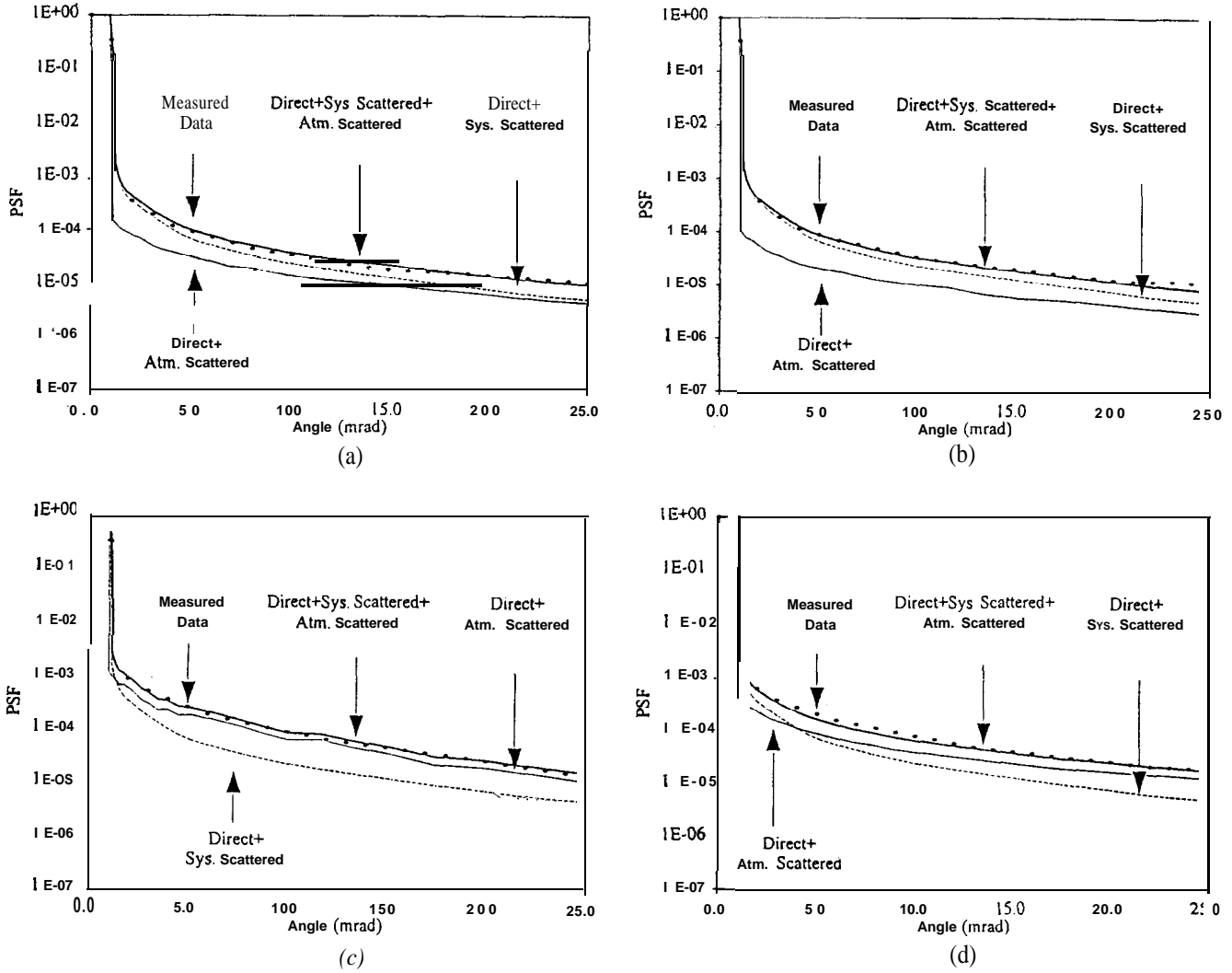
Figure 6: Comparison of the measured PSF by the "Dual Channel" radiometer with the predicted PSF according to the presented model. The comparisons are for measurements made at an urban aerosol loading of (a) $k_e^t \approx 0.1$ km-l; (b) $k_e^t \approx 0.2$ km^{-1}; and at rural aerosol loading of (c) $k_e^t \approx 0.4$ km^{-1}; (d) $k_e^t \approx 0.6$ km-'.

5. CONCLUSION

A physical model, which describes the effect of the radiation scattered by the aerosols and molecules in the atmosphere on an imaging system, is presented. This model explains how the field of view, the dynamic range and other characteristics of the imaging system as well as the turbidity of the atmosphere affect the measured PSF of a distant point source. It is found that for common imaging systems in general atmospheric conditions, the processes of atmospheric scattering and absorption do not contribute to spatial blurring of the recorded images. Only at extreme conditions of atmospheric turbidity (such as dense fog, rain or sand storm) and for imaging systems with wide FOV, the atmospheric scattering will blur the images as seen by them.

The agreement of theoretical predictions with the measured data in our field measurements is very good. Figures 6 demonstrate the ability of the proposed model to predict quantitatively the relative contributions of the direct, atmospheric scattered and system scattered components.

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